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ABSTRACT

Past research has uncovered few broad abilities that underlie high level motor skill. In this paper attempts to isolate three different abilities of potential relevance to skill are described. No evidence was found for a general time-sharing ability in common to different kinds of tasks. Modest evidence was found for a trait of attentional flexibility. That trait could potentially be of use in predicting success on skills that require rapid shifts of attention because of rapidly changing task demands. Finally, the rate of repetitive activity is correlated across different muscle groups. For example, finger tapping speed is correlated with foot tapping speed, suggesting a common rate limiting factor. In turn, those rates predict handwriting speed and, according to Book (1924), championship typing speed.

Explorations of Individual Differences Relevant to High Level Skill[1]

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Consider fast action motor skills such as piloting a jet plane, driving a car in Rome, playing basketball, boxing, and the like. What accounts for the enormous success enjoyed by some people in such skills while others remain relative novices? One view assumes the extraordinarily successful person has exceptional perceptual or motor capabilities--indeed, this may be why such skills have for so long been called perceptual-motor skills. But the perceptual-motor view has not been very useful for predicting individual differences in capability. Factors such as reaction time, movement time and perceptual sensitivity seem not to correlate much, if at all, with skill success (Marteniuk, 1974). With practice, skill in a task appears to become more specific to itself, and less predictable by other perceptual-motor factors (Fleishman, 1966).

An alternative view posits that task success largely results from practice. There is little doubt that practice is extremely powerful in its influence on skill. Moreover, recent conceptions of nonmotor skills such as chess, physics problem solving, mental arithmetic, and cognitive mapping have begun to yield understanding of what practice does (Chase & Chi, 1981). In essence, practice yields both an increasing number of patterns or situations that people recognize and each pattern automatically prompts a specific routine or set of procedures. In one now well known demonstration, Chase & Simon (1973) briefly presented 24 chess pieces arranged according to a real mid-game position. A chess master was able to reproduce about 16 of the positions, a lesser class A player about 8, and a novice only 4. The superior feat of the chess master seems specific to knowledge of chess patterns. When asked to reproduce the position of 24 randomly arrayed chess pieces, the master, if anything, performed worse than the novice. This view of practice is quite consistent with the notion of task specificity. The gradual acquisition of patterns and procedures would render skill specific to the task practiced.

Nevertheless, the possibility remains that people differ in some general abilities that account in part for differences in skill. High speed tasks the like of piloting, driving, basketball, and boxing are characterized by several things occurring at one time and by very rapid changes in what is happening. Both factors place a heavy demand on decision making capabilities. In addition, such tasks typically require maintaining a sense of direction in a rapidly changing spatial layout and they require exquisite timing. Conceivably, individual differences in the ability to time-share more than one task, flexibility of shifting attention from one portion of a task to another portion, and sense of direction are related to skill prowess. This paper summarizes our investigations of two of these hypothetical abilities (time-sharing and attentional ability). Additionally some promising preliminary work on the speed of repetitive activity will be reported.

Although ultimately one would wish to predict performance on complex tasks, initially we have emphasized the construct validation of the traits in question. To do this we developed alternate tasks to measure the presumed general ability. If a general ability indeed exists, then the different measures should correlate with one another. If the ability indeed has construct validity, then selected measures can be used to predict task success. As will be seen, time-sharing does not seem to be a unitary trait; hence it would not be useful to investigate whether such an ability is predictive of high level skill. In contrast we provide modest evidence for a trait of attentional flexibility. And early results are very encouraging for individual differences in the speed of repetitive activity.

Before discussing each of the three abilities investigated, the general approach taken in most of these studies is described.

An Information Processing Approac to Individual Differences

For the most part, these investigations make use of what may be called an information processing approach. Such an approach is now becoming relatively common in analysis of individual differences in cognition. The essence of the approach applied to cognition is provided by Hunt, Frost and Lunneborg (1973). Two primary features distinguish an information processing approach. One feature concerns the attempt to isolate constituent processes that underlie a task. The second feature, closely interconnected with the first, emphasizes theoretical rationale in selecting tasks and processes to be studied.

In the traditional correlational and factor-analytic approaches to individual differences, scores from complete tasks typically are correlated with one another. For example, reaction time might be correlated with some measure of athletic ability. A correlation between task scores implies that some processes are in common, but such correlations typically are found to be low by virtue of the fact that tasks typically differ in a variety of processes as well. The information processing approach attempts to alleviate this problem by deriving scores intended to reflect only the process in question. Process scores derived from different tasks should correlate highly because only the features common to the tasks are compared. Consider, for example, a process of switching attention. Reaction time is taken for cases where subjects have no particular expectation and for other cases where they expect a particular stimulus and either the expected or unexpected one occurs. The benefit of expectancy and the time to switch to unexpected stimuli can be derived by subtracting reaction times from the neutral case. Note that the derived score is not reaction time but a difference score based on reaction time, and it is the derived score that would be correlated with some other derived score.

Typically, the isolation of a process score involves a variant of subtracting two conditions that differ only in a process or duration of a process. Sometimes that subtraction is disguised as a parameter obtained from curve fitting (e.g., slope of a function,) but nevertheless the logic is basically subtractive.

The measurement of isolated processes is an ideal not often met in practice. Imperfect isolation of processes likely accounts for many correlations being smaller than otherwise expected.

The technique of process isolation will be seen most clearly in this paper in the analysis of time-sharing and flexibility.

The second feature of an information processing approach is that it is theoretically motivated. What this means is not necessarily that a tight theory exists regarding underlying processes, although that may be the case. Rather it may be that the results of correlational approaches are used to uncover processes in much the same way as with conventional experimentation. Hypotheses are constructed regarding the existence of certain processes, and tasks are selected in accordance with those hypotheses. The analysis of repetitive movement in the final section of this article makes less use of process isolation, but at least in the long run it is theoretically motiviated in an information processing sense.

Traditional approaches to individual differences typically involve a very large number of subjects in order to derive stable estimates of correlations. The number of subjects in our studies, however, has been small, often 15-30 people. One reason is simply pragmatic. The paradigms that we've used are quite time consuming, making large numbers of subjects impractical. A second reason though involves research strategy. The "expectation" in the information processing approach is for high valued correlations because one intends to correlate process scores. If the correlation is high, then relatively few subjects suffice to demonstrate it. If, on the other hand, correlations are small, it means that something is wrong either with the motivating theory or with methods. This prompts a concern then, not with solidifying the magnitude of a small correlation, but improving methods and theory. In turn, as in typical experimentation, one is led to conduct several studies involving rather few subjects. Of course, a danger exists. Rather modest "true" correlations will often fail to materialize with small numbers of subjects in that promising leads may be lost for lack of statistical power.

Time-Sharing Ability

Are some people better equipped to handle the overlaod of simultaneous task demands than are other people? A demonstration of a general time-sharing ability requires this logic: Measure the ability to jointly perform tasks A and B and adjust that score by the ability to perform each task alone so that the derived score reflects the added difficulty of performing the two together rather than single task difficulty per se. If a general ability exists, then the derived score should correlate with the ability to time share yet two other tasks C and D.

Sverko (1977) applied this logic to the joint performance of different pairwise combinations of four tasks--pursuit rotor, visual choice reaction time, mental arithmetic, and auditory discrimination. No evidence was found for a general time-sharing ability.

Hawkins and colleagues (Note 1), as part of our general project of individual differences, tested for a general time-sharing ability in a particularly stringent manner.[2] They used the psychological refractory period paradigm. A signal is presented that requires one response. But either before the response can be emitted or a brief time after the first response, a second signal is presented that also must be responded to but with a different response. The interval between the first and second signal varies between 0 and 1200 millisec. When the second signal occurs prior to the first response, the second response is delayed, hence the term psychological refractory period. A measure related to the delay specifies the amount of time sharing: The less the processing of the first signal delays processing the second, the greater time-sharing ability. The central question, therefore is whether time-sharing ability for one combination of two signals and responses correlates with time-sharing ability when the nature of the signals and responses are changed. What makes the analysis particularly appealing is that the strategy by which subjects interweave the two tasks can be held rather constant for all task combinations simply by ensuring that the subjects deal with the first signal before responding to the second. Thus, time-sharing primarily is reflected in second task processing rather than in some unknown mix of emphasis on the two tasks. Moreover, time-sharing analysis of all task combinations can be based on a common metric--reaction time.

To test for a general ability, the Hawkins group varied the nature of the signals and response. The second stimulus was always a visually presented digit, but the first signal could either be a visually presented letter (H or N) or a tone (800 or 1200 Hz). The response to the second signal was always a key press with one of two right hand fingers, but the first response could be either manual (key press with middle or index finger of the left hand) or vocal (spoken word "red" or "green"). Finally, the first task was rather constant in difficulty, always involving two signals and two responses, but the second task was easy or difficult. For the easy second task, two visually presented digits (2 or 3) corresponded to the two right-hand key presses; for the difficult second task, eight visually presented digits were assigned to the two fingers on the right hand (digits 2, 5, 6 and 9 to the index finger and 3, 4, 7 and 8 to the middle finger). Altogether then, there are 8 combinations of the two tasks depending on whether the first signal is visual or auditory, whether the first response is manual or vocal and whether the second signal-response combination is easy or difficult. Each of these eight combinations involving different tasks 1 and tasks 2 were run on separate blocks of trials. Eighteen subjects were run over all combinations in one experiment and another 22 subjects performed in a replication experiment.

Restating the central question: Does the difficulty that a person has in dealing with one combination of two tasks predict the difficulty that same person has with another combination? Predictability would be evidence for a trait of time-sharing ability.

A measure that reflects difficulty of time-sharing must deal with two conceptual problems. First, reaction time to the second signal is not appropriate, for that measure can reflect difficulty not just in time-sharing but difficulty of processing that signal itself. Define $RT_{2(1200)}$ as reaction time to the second signal when it onsets 1200 millisec. after the first. By that time the first response has been made, so there is no time-sharing of the two signals. $RT_{2(1200)}$ therefore is a control for second signal difficulty. $RT_{2(0)}$ is defined as second signal reaction time when the second signal occurs at the same time as the first. Because subjects are instructed to respond to the "first" signal first, its reaction time is normal and $RT_{2(0)}$, is elongated. The degree of elongation is obtained by $RT_{2(0)}-RT_{2(1200)}$.

The second conceptual problem is that delay of the second signal is determined not just by the degree to which the two processes can be time-shared, but by the difficulty a person has with the first signal on its own. That is a person who has a slow reaction time to the first signal (RT_1) will also be additionally delayed in dealing with the second signal. Clearly an adjustment must be made for this factor and it takes the following form: $(RT_{2_{[0]}}-RT_{2_{[1200]}}) - RT_1$. Typically, this number is negative. Reversing sign gives a number that denotes the amount of overlap in the processing of signal 1 and signal 2.

Dividing the term by RT_1 normalizes the equation so that the time-sharing measure ranges from 0, or no time sharing, to 1.0, or perfect time-sharing: $e_{ts} = \frac{RT_1 - (RT_{2_0} - RT_{2_{1200}})}{RT_1}$. In the more complete paper by Hawkins and Olbrich-Rodriguez (in preparation), complete data on RT means and the actual time sharing values are presented. Here we deal only with correlations of the time sharing measures from different task combinations.

Table 1 shows the average corrrelations across subjects between different task combinations for two different experiments. Note that some task combinations are the same on all but one variable. For example one combination could be: first signal visual, first response manual and second signal difficult. Another combination of the two tasks could be identical except that the second task is easy. The correlation then would relate how well time-sharing on the one combination predicts time-sharing on the other combination that differs on only one variable. In each of the two experiments there are 12 such correlations, which are averaged for Table 1. In other cases the two different task combinations being compared would differ on two of the variables but be the same on one. Again there are 12 different correlations per experiment. In yet a third case, no variables would be in common between the two task combinations being compared. For example, the task combination of signal 1 auditory, response 1 vocal, and signal 2 difficult differs on all three variables from the combination signal 1 visual, response 1 manual, and signal 2 easy. In this case there are 4 correlations per experiment to be averaged. Table 1 is broken down for correlations of time-sharing efficiency between tasks that differ on 1, 2 or 3 variables.

Insert Table 1 about here

The striking result is that ability to time-share one combination of tasks has virtually no predictability for the ability to time-share another combination of tasks as long as those task combinations are quite different from one another. Of the eight correlations that make up the two average correlations involving 3 task differences, none are significantly different from zero. This lack of predictability from one combination to the other occurs despite the fact that all tasks emphasize that the first signal be responded to before the second, (reducing strategic options), all tasks share a common reaction time metric, and all conditions conform to the discrete trials paradigm, commonly called psychological refractory period. When two task combinations being correlated differ in two ways, the mean correlation is slightly greater. Out of the 24 correlations in the two difference condition that make up the averages in Table 1, only 8 are significantly different from zero at the .05 level of confidence. It is only when two different task combinations are very similar to one another with only 1 difference that individual differences in time-sharing performance in one combination begins to be more predictive of individual differences on another. Seventeen of 24 correlations that went into the "1-difference" averages of Table 1 are significant at the .05 level of conficence.

The failure to find correlations of time-sharing ability across tasks that differ in input mode, response mode and difficulty strongly suggests that no <u>general</u> time-sharing ability exists.

In subsequent work, Hawkins and his colleagues (Note 2) investigated a somewhat different interpretation of time-sharing. Subjects in the study just described successfully responded to the first signal uninfluenced by the time of occurrence of the second. That is, RT_1 was more or less the same regardless of whether signal 2 occurred at the same time as signal 1, slightly later, or after signal 1 had already been responded to. However, in that study, there were no occasions on which signal 1 occurred in blocks of trials without signal 2 at all. Subjects always knew a second signal would occur, but not exactly when. In the more recent work, the Hawkins group ran controls in which signal 1 occurred either alone, in conjunction with an easy second signal, or in conjunction with a difficult second signal. In the latter two conditions, reaction time to signal 1 was taken only from the case where the second signal occurred 1200 millisec. after the first. Thus, any lengthening of RT_1 must be due, not to time-sharing the processing of two signals, but rather to preparation for a second signal. Reaction time to signal 1 was 496 millisec. when it occurred alone, 624 millisec. when it was followed by an easy second signal and 635 millisec. when followed by a difficult second task. This deficit when expecting a second signal could be termed <u>preparation cost</u>.

Is preparation cost a general factor? Are some people better than others, not at time-sharing on line, but rather in showing less preparation cost whether or not two tasks actually overlap in processing time? The same logic was pursued as in the preceding study: preparation cost was measured for each individual for eight different combinations of first and second signal.

The mean correlations of preparation cost score across individuals for task comparisons that differ on 1, 2 or all 3 of the variables are .46, .32, and .14 respectively. As before, there is no evidence for a general preparation cost factor. When preparation cost on one combination of tasks is compared with preparation cost on a different set of tasks that differ in three ways the correlations that go into the average are near zero and none are significant. Only when the task combinations are quite similar do they begin to correlate. Seven of 12 preparation cost correlations are significant ($p<.05$)when the pair of task combinations being correlated differ in only one way.

The conclusion that no general time-sharing ability exists was further bolstered in yet a third study (Hawkins, et.al in press) that involved fewer assumptions about the appropriate time-sharing measure. Again, there were two signal sets, 1 and 2. These were run alone as controls and also in a condition where signal 2 followed signal 1 at some interval ranging from 0 millisec. to 1200 millisec. The measure of time sharing efficiency was simply the total deficit when the tasks were run together, as opposed to separately,and expressed as a ratio:

$$\text{ets} = \frac{RT_1 \text{ alone} + RT_2 \text{ alone}}{RT_1 \text{ paired} + RT_2 \text{ paired}}$$

Rather than running each subject on 8 different task combinations, they were run only on two. In one combination signal 1 was visual, response 1 manual and task 2 consisted of two easy 1:1 stimulus-response mappings. In the other combination, three things were changed: signal 1 auditory, response 1 vocal, and task 2 consisted of two difficult, 4:1 stimulus-response mappings. The correlation of the measures of time-sharing ability between the two combinations was -.041. Again, there seems to be no evidence for a general time-sharing ability.

Normally one does not pay much attention to essentially negative results. Such should not be the case here because many people have thought that high level of skill on fast action tasks might be partly predicted by time-sharing ability. The Hawkins studies are notable in arguing against that likelihood by controlling to a major degree the strategies by which subjects interweave the tasks, by using a common reaction time metric throughout, and by examining three different interpretations of what is meant by time-sharing. While particular task combinations might be useful in predicting particular skills, we must look elsewhere for general cognitive abilities that might usefully predict skilled performance.

Strategies of time-sharing were stringently controlled in these experiments: The signals were discrete pairs that were responded to in a set order. Many real life tasks are ongoing and the performer must interweave them in some manner. It is conceivable that different modes of interweaving would be more efficient than others. Thus, while people may not differ on time-sharing ability given a controlled strategy, they might differ on time-sharing skills given flexibility of strategy. Such skills might be general to different combinations of tasks. While Hawkins found no evidence for a general time-sharing ability when people were forced to process tasks in a particular order, Damos & Wickens (1980) found that people differ on stable modes of interweaving tasks that cut across tasks. Thus, it is conceivable that a time-sharing skill involving continuous tasks can be trained.

Beyond the practical implications regarding prediction of skill proficiency, the Hawkins' studies have a major theoretical implication. In the recent past, many attention theories could be classified as general capacity theories. The notion was that tasks to varying degrees drew on some common pool of capacity, and it was insufficient capacity that produced interference among tasks. But these studies join a growing body of evidence against a general capacity theory, (e.g. Navon & Gopher, 1979) and indeed, may provide some of the strongest evidence. All the tasks used by Hawkins and colleagues do interfere with one another. But if the amount of interference simply reflects the amount of capacity an individual has available, then interference with one combination of tasks should predict interference with another. The fact that such predictability doesn't occur suggests instead that specific features of tasks determine the amount of interference and that the difficulty a person has with processing one kind of feature says little or nothing about the difficulty of processing another type of feature.

Flexibility of Attention

One characteristic of many fast-action skills is that the crucial demands of the task often shift dramatically. In sports a sudden opportunity may appear or an opponent may do something that catches a player off guard and requires a change in response. In automobile driving or piloting, the operator who can quickly switch attention to an unexpected event may prevent an accident. Conceivably some people are better than others at rapidly switching attention from one source to another. Such a general ability we will call flexibility of attention.

Gopher and Kahneman (1971), and Kahneman, Ben-Ishai, and Lotan (1973) devised a dichotic listening task involving two parts. In the first part a high or low tone indicated which ear to report digits from in a string of digit-word pairs. Then with no break a second tone recued which ear to report digits from in a series of digit pairs. Report errors from part 1 had little predictive power for skill but errors in part 2, following the second tone, correlated modestly with number of accidents among Israeli bus drivers, with flight school success of pilot trainees, and with skill levels of air force pilots. Kahneman, Gopher and colleagues speculated that part 2 errors were predictive of skill success because only part 2 required rapid switching of attention from the previously committed state in part 1. These impressive demonstrations were the germination point for our studies of attentional flexibility.

Our general strategy was to devise different speeded situations that at times required a rapid switch of attention. If a general trait of flexibility exists, then measures of flexibility extracted from one situation should correlate with measures extracted from another. Again, our attempt at this stage is not to correlate flexibility with high level skill but rather determine whether there is validity to the construct of flexibility.

In the first study (Keele, Neill, & DeLemos, Note 3) one task was a <u>dichotic listening</u> task similar to that in the Kahneman, Gopher, et al. studies. It was constructed by Dick Pew of Bolt, Beranek, and Newman and kindly lent to us. Pairs of color names or a color and a digit were presented through earphones with one number of each pair to an ear. The string of pairs was started by a high or low tone indicating which ear to report digits from. After several pairs a second tone required reassessment of which ear to report from, and the series continued at the fast rate of two pairs per second. Altogether four tones occurred in a block of trials, requiring three reassessments of which ear to attend to. The measure of flexibility was errors in reporting the correct digits.

All the other tasks used reaction times to derive the measures of flexibility. One task was Priming. A warning signal preceded by 500 milliseconds the occurrence of one of four imperative signals, a red light, a square, a triangle, or a trapezoid. Each imperative signal was assigned a different key press response. On half of the trials the warning was a neutral "plus" which meant that each signal was equally likely. On the other trials the warning was the word red, indicating a 70 percent chance the imperative signal would be red. If the red light actually occurred, reaction time was typically fast. Subtracting reaction time to the expected occurrence of red from the condition of neutral expectancy yields a measure of benefit from the priming cue, i.e., the degree to which one can bring attention from a neutral state to bear on a particular alternative. On the other hand, if following the red prime the red light does not occur, reaction time is slowed, yielding a cost relative to the neutral situation. Both cost and benefit are measures of flexibility that presumably reflect the mobility of attention shifts.

A second reaction time task, Rare Event, used the same response stimuli--red light, square, trapezoid, and triangle--and the same response assignments. On 99% of all trials, one of the three forms occurred. Response to one signal was followed 20 msec later by another stimulus. On only 1% of the trials, averaging once every two blocks of trials and 12 times a session, did a red light occur. Because in the context subjects were expecting forms, reaction time to red lights suffered large cost. Cost to the red light can be calculated by subtracting the neutral reaction time to red lights in the priming study from reaction time to the red light when it rarely occurred in the rare event task. Cost calculated in this manner tended to be four or five times larger than cost in the priming study.

Both preceding tasks measured flexibility by the additional time required to respond to an unexpected signal. The Alternation task required switching set but not in an unpredictable manner. Subjects were presented with six signals. Three colored lights--red, green, and yellow--were assigned to keys operated by the left hand and three forms--square, triangle, and trapezoid--were assigned to keys operated by the right hand. In pure blocks subjects expected and responded only to colors or only to forms. In alternating blocks subjects responded to both colors and forms, but the two signal types strictly alternated. Response to a color was followed by a form and vice versa.

Should alternating blocks be viewed as six-choice or three-choice? If subjects efficiently switch attention, then the alternating condition is like three-choice. But if they fail to constantly use the predictability inherent in the situation and alternate attention, the task is like six-choice. In general alternating reaction time minus pure block reaction time yields a measure of flexibility.

In the Alternating task, two different response-stimulus intervals were used. At the fast rate only 50 msec transpired between one response and the next stimulus. At the slow rate 750 msec transpired. The slow rate provides time for switching set, but even at that rate all subjects had slower RTs in the alternating condition than in the pure block condition. This result suggested exploring two measures of flexibility. One measure was simply alternation reaction times at the fast rate minus pure block reaction times at the <u>fast</u> rate. The other measure adjusted the first one by additionally subtracting <u>slow</u> rate alternating RTs minus pure RTs. The rationale of the adjustment was that some people do not alternate attention very effectively even at slow rates where ample time should be available. The adjusted measure therefore reflects flexibility that was due to the high rate of action rather than one's reluctance to optimally prepare set.

If people differ from one another on a general trait of flexibility, then measures of that trait derived from different tasks should correlate with one another.

Table 2 shows the correlations between the different measures of flexibility.

Insert Table 2 about here

The major diagonal shows the reliabilities, which are adequate except for the very low reliability of the priming cost measure. Priming cost reliability is unstable over successive days of testing. In turn unreliability may explain why prime cost does not correlate with other measures of flexibility.

Further examination revealed a problem with the dichotic listening measure of flexibility. Recall that the reaction time based measures of flexibility are all adjusted for a baseline reaction time so that they reflect attention switching and not reaction time per se. In fact, average reaction time does not correlate to an appreciable degree with the reaction time based measures of flexibility. On the other hand, the dichotic listening score correlates even more highly with average reaction time ($r = .51$) than with the other measures of flexibility. When average reaction time is partialed out of the correlations involving dichotic listening, little predictive validity remains. One interpretation, therefore, is that dichotic listening is highly sensitive to processing speed. Because the task proceeds at a fast pace, subjects who are slow will tend to make errors whenever they get behind in processing, and that most likely will occur when a tone calls for reassessment of the ear requiring attention.

The remaining correlations among prime benefit, rare event cost, and the cost of alternating between two signal sets, while not large, do suggest a common trait of flexibility. However, given the logic of the information processing approach in which scores are derived to reflect particular processes, one might query why, if a general trait exists, the correlations among measures derived from different tasks are not substantially higher. We have conducted several additional studies that attempted to alleviate a variety of problems. In general those studies yielded comparable results to those of the first study; none yielded substantive improvement. Rather than detailing each study, therefore, it is more fruitful to discuss problems with particular measures and suggest which tasks are most appropriate.

One problem concerns speed-accuracy tradeoff. The reaction times for individual people depend in part on the error criterion adopted. Although the flexibility scores are derived by subtractive procedures so that absolute reaction time is not used, speed-accuracy tradeoff might in some way interact with the derived scores. One solution would be to map out speed-accuracy functions for each person, but for reasons of time and economy that is not practical when many subjects, tasks and sessions are required. Our adopted approach has been to specify an accuracy range for subjects to stay within so that they differ from one another primarily on speed. Although helpful, this strategy has not been completely successful, and residual differences among people in speed-accuracy tradeoff still contaminates the results, presumably lowering correlations between the different measures.

A related but more serious problem concerns not overall speed but rather strategic differences in how much people emphasize different components of the task. This problem is particularly serious in the priming paradigm. The more people rely on the validity of a prime that cues them for a particular signal, the greater the benefit from using the cue. But when the unexpected signal occurs, cost is large. In all our studies, cost and benefit have been highly correlated, largely due, we believe, to this strategic effect. Simply by instruction, the magnitude of both cost and benefit can be dramatically altered. We have not identified a way of solving this problem of the priming paradigm. It may exist as a problem in the rare event paradigm as well, though it would appear not so serious. In the rare event paradigm, the primary task occurs so frequently that subjects have little option but to expect primary task signals. The problem may be least serious in the alternation task in which unexpected signals do not occur. On that task, only benefit occurs from expecting the appropriate signal set. Despite the fact that alternating attention is only beneficial when the signal set alternates, subjectively it is very difficult to continually switch attention back and forth and hence it appears to differentiate people.

A third probelm concerns reliability. Lack of reliability has stemmed not so much from too few observations as much as changes over time, particularly for the cost measure in the priming task. Some people may initially show large cost to an unexpected signal, but may be less hampered after a session of practice. The changing nature of the factor poses difficult questions regarding what stage of practice is best for extracting a measure of flexibility.

The fourth major issue involves fault with the assumption that the derived measures of flexibility reflect primarily one process. Again, this problem seems most serious for the priming task. At least three processes appear to influence benefit following a cue to expect a particular signal.

One is what Posner and Snyder (1975) call an automatic or pathway activation effect. Even with no investment of attention, the occurrence of a cue related to a signal sensitizes the nervous system to a subsequent occurrence of that signal. Second, investment of attention on an expected signal source yields additional benefit, and, in Posner and Snyder's conception, it is the source of cost when an unexpected signal occurs. And third, the initial investment of attention appears to produce residual costs and benefits even when attention is withdrawn from the initial cue (McLean & Shulman, 1979). These residual effects appear analogous to criterion shifts in signal detection theory, and they help explain error patterns that occur.

These various considerations suggest that the priming procedure is a poor candidate for measuring attentional flexibility. The rare event procedures and the alternation procedures, though raising some problems of their own, may be better candidates. The alternating procedure, therefore, was further investigated.

The strategy in the flexibility study already reported was to compare measures of flexibility from different paradigms, but except for the dichotic listening task, the signal and response sets were quite related. The studies of time sharing pursued a different strategy: Does the trait of interest emerge when a common paradigm is used but the nature of the signals and responses are varied? This question is quite important, for it is conceivable that different kinds of signals and responses would require different processing systems and hence not tap a common trait. This strategy was, therefore, applied to the flexibility problem.

Subjects performed on two different task pairings. In one pair, one of the signal sets used the letters A, B, C and D with two letters assigned to each of two response keys operated by one hand. The other signal set used the digits 1, 2, 5 and 6 mapped into two response keys operated by the other hand. In one condition the two subtasks were performed alone on separate blocks of trials. In the other condition the two signal types strictly alternated on successive trials. Flexibility in switching attention was measured by subtracting reaction times in the single task cases from reaction time when the two tasks alternated. These scores for 22 subjects were then correlated with the same scores derived from the other pair of tasks. In the other pair, the visual letters were replaced by a set of four auditory sounds (high frequency tone, low frequency tone, buzz, trill) and the sounds were mapped into two vocal responses ("red" and "green"). For the other task of the pair the set of digits was enlarged to include 1, 2, 3, 4, 5, 6, 7 and 8, which again were mapped into two key press responses. This manipulation made the task more difficult. Altogether, the two different task pairings differed in stimulus mode, response mode, and difficulty level.

The Pearson correlation of the flexibility scores derived from the two task pairings was .48 ($p<.025$). This basic result has been replicated in an additional experiment.

Although again not large in magnitude, the correlation suggests a trait of flexibility common to two task combinations that though similar in paradigm differ in the nature of the signals and responses, and in their difficulty. Together with the earlier results that use similar signal-response sets embedded in different paradigms, these results fulfill the first step of attempting to determine whether cognitive traits are useful in predicting success on high level skill. They provide some construct validation of the trait of attentional flexibility.

Following construct validation it remains to show that selected measures of flexibility correlate with selected measures of a fast-action skill. We have not made successful inroads on this problem; the task is rather formidable. First, given that the correlations among different measures of flexibility are themselves moderate in magnitude, it is unlikely that any one of them would correlate highly with performance on some particular fast action skill. Second most skills undoubtedly are influenced by numerous abilities. Ideally, predictions would be based on a battery of predictive variables, but to this point attentional flexibility is the only cognitive factor for which we have found construct validity. Moreover, most fast action skills can be highly influenced by a variety of non-cognitive factors, such as strength, muscle composition, size of body and the like. What scores should one extract from a real life skill that might relate to the predictors?

Individual Differences in the Rate of
Repetitive Activity

Recently we have begun to investigate individual differences of quite another sort--the rate of repetitive activity. Speed on many tasks seems constrained by the rate at which a person can serially activate a succession of movements. For example, recent conceptions of handwriting (cf. Keele, 1981, for a review) have suggested that writing is controlled by three sets of muscles. One muscle set simply provides steady left-to-right movement. A second pair of muscles produces up-down movement on a page, and a third set operates orthogonally to the second, producing back and forth horizontal movement. The "program" for a letter can be viewed simply as the time specifications that determine for how long and in what time relations the two orthogonal muscle sets are activated. By this view, handwriting speed might be constrained by the rate at which one can produce repetitive movements by the relevant muscle sets. Likewise, the speed of typing might be constrained by the speed at which one can repetitively activate the fingers.

The initial question we have asked is whether the rate at which people can repetitively produce movement correlates across a diversity of muscle groups. In other words, can people be characterized by a general speed factor that cuts across different movement systems? Second, if such a general speed factor exists, does it tell us anything useful about the speed at which people perform tasks like writing or typing?

In one experiment, 15 people produced tapping movements as rapidly as they could with the forefinger, the thumb, movement about the wrist, movement about the elbow, and movement of the foot about the ankle. In each case the number of taps was counted in four different 7-second bouts of tapping. Tapping duration was held to 7-second bouts because when movement is at maximum speed and restricted to one joint, fatigue sets in very rapidly.

Table 3 shows tapping speed expressed both as millisec. per tap and taps per sec. Finger, thumb and foot are tapped about the same speed of

(Insert Table 3 about here)

5 taps per second averaged over all 15 subjects. The wrist and arm are faster at about 6 taps per second.

The question of central interest, however, is whether tapping rate correlates across the different systems--i.e., do people who are slower with one system tend to be slower with another system. Table 4 shows inter-correlations of tapping rate among the five different movement systems.

(Insert Table 4 about here)

The major diagonal shows the reliability of the measures for each system and below the major diagonal are the uncorrected correlations. All the correlations in Table 4 between the different systems are significant at the .01 level of confidence. The magnitude of the correlations are limited by the reliabilities, but an estimate of what the correlations would be were the scores perfectly reliable can be obtained by applying the standard correction for attenuation. The corrected correlations are shown above the major diagonal in Table 4. The corrected correlations are quite high, the lowest being .68. Perhaps most important, foot tapping speed correlates highly with tapping speeds of all elements of the upper

These results suggest that tapping speed is a rather general factor that cuts across at least several different muscle systems. We have replicated this essential finding in other studies.

Perhaps the more interesting question, however, is whether tapping speed is predictive of performance on important human skills. In the study just reported, we not only asked people to tap with different muscle groups, but we also asked them to write a sentence several times at their normal writing speeds. We asked for normal writing speeds because it is not clear how one could establish maximum speeds. As writing speeds up beyond the normal range, it quickly becomes illegible. There is no clear criterion as to when it should no longer be called writing. We assumed, therefore, that a person's normal writing speed might be self-adjusted to reflect their maximum speed of reciprocal movement. Two kinds of writing were examined: small writing with the hand on lined paper and large writing with arm movements, analogous to writing on a blackboard.

Table 5 shows the correlations between tapping speeds of the different muscle systems and handwriting speed. The left column shows uncorrected correlations, and the right column shows correlations corrected for the reliability of tapping speeds but not corrected for reliability of handwriting speed, as we did not measure the latter. Despite the fact that handwriting speeds are self-determined as normal in speed, they are quite well predicted by tapping speeds. Perhaps of greatest interest is that foot tapping predicts handwriting speed as well as does speed of the articulators actually involved in handwriting. Tapping speed averaged over all the articulators correlated .63 with handwriting speed.

(Insert Table 5 about here

In constrast to handwriting, arm writing speed failed to correlate significantly with tapping speed of any of the movement systems. The correlations were not only uniformly low and near zero, but inconsistent in sign. We speculate that the different results with handwriting and arm writing are due to differing amounts of practice. College age subjects have had 12 or more years' practice with handwriting. With such extreme practice, it is likely that speed is constrained not by lack of practice but by intrinsic speed of the movement system. On the other hand, many college age subjects have had little practice in arm writing so that speed may be limited by familiarity with the task. Some justification for this view is provided by the relation between typing speed and tapping speed.

Some studies have failed to find a relation between typing speed and tapping speed in high school students (cf. Seashore, 1950). But high school students are not very practiced and clearly other factors such as motivation and knowledge of language properties would have sizeable influences on typing speeds. Their speed undoubtedly is less than they would be capable of with extreme practice. Book (1924), however, tested participants in an international typing contest. The contest included past and present world and country champions in several professional and amateur categories. Moreover, Book's colleague Nicholson (Note 4), had previously established norms for tapping rates of the finger, wrist, elbow and shoulder for over 2000 subjects. Norms were based on up to 25 males and 25 females for each year of age ranging from 16 to 75 years of age. Thus, tapping rates of each typing champion could be compared to a normative group matched exactly for age and sex. World and ex-world typing champions averaged about 25-33% faster tapping than their matched controls. Faster tapping among champions was present not only for finger and wrist tapping, but if anything was more pronounced for tapping about elbow and shoulder joints. Champions in non-professional categories likewise showed superior tapping rates, though not as marked as for the professional world champions. This appears reasonable from a practice viewpoint. Presumably tapping speed in the more practiced professionals would more likely be constraining to typing speed.

Finally, Book studied 55 students who participated in a college level typing course. Though specific correlations are not available from Book's study, tapping rates established both before and after the course were related to the typing speeds eventually achieved. This study of college students is additionally important because the before and after analysis showed tapping speed not to change with typing practice. This would suggest that the high tapping speeds of world champion typists is not a product of typing practice, rather tapping speed appears to be the primary limiting factor.

It appears, therefore, that speed of reciprocal activity is not only related across several muscle groups but also is related to speed on at least two important human skills, handwriting and typing. It remains yet to be seen just how general this speed factor is. In addition to writing speeds, we've also explored the relation of tapping speed to vocal speed. In one case we asked people to count repeatedly from 1 to 10 as rapidly as possible. In another case, we attempted to assess normal speech rates by having people read aloud at their chosen speed a written paragraph. In neither case did vocal speed relate to tapping speed. It may be that speed of the vocal system is under independent control. On the other hand, the tasks chosen may provide poor tests of the hypothesis. Another important muscle system that we have not studied is that involved in locomotion. Is the maximum speed at which the legs can be alternated in running related to tapping speed? One reason for thinking they may not be related is that locomotor activity appears largely under spinal control in which speed of locomotion can be controlled by <u>tonic</u> input to the spinal cord (Grillner, 1975). Nonetheless, that would appear to be an important issue to investigate.

Possible Mechanisms Underlying the Speed Factor

What kind of mechanism might underlie the correlations between maximum rates of reciprocation of different muscle systems? One possibility is that the maximum rate depends on biomechanical factors and these might be related in the same individual. For example, a person with a large foot might also tend to have large fingers, hands, and arms, or properties of the muscles might be similar for a given individual. One specific hypothesis is that the articulators are like pendulums. In a pendulum the period of oscillation depends on the distance of the center of gravity from the rotation point. Thus, movement about the elbow should be much slower than finger movement, but in fact the reverse is true. Moreover, one can drive movement about the elbow at faster than the natural period of oscillation. Thus, there must be some other driving force that can oscillate at a faster frequency than the natural resonance.

A second biomechanical notion assumes that maximum tapping rate depends on renewal rate of the muscle's energy source. It seems unlikely from that view that different groups of muscles would have similar tap rates. Somewhat more problematic, the maximum rate of finger tapping is nearly independent of the amplitude (Bryan, 1898; Fenn, 1938). Larger excursions presumably involve greater expenditures of energy so it would appear that the rather similar tapping rates at different excursions are determined by some factor other than an energy limit.

A related idea is that the muscles are limited in the rate of buildup of tension. This seems an unlikely limit because again when amplitude of movement is increased, cycle time remains rather constant implying a faster buildup of tension. Moreover, Ghez (1979) and Freund and Büdingen (1978) report that the time to reach peak force in single flexion movements is rather constant for movements of different amplitude. This in turn implies that larger amplitude movements involve a faster buildup of tension. Thus, the constant feature is not rate of tension increase but rather the duration of buildup.

The various factors--similar rate for movement systems of widely different sizes, similar rates for movements of different excursion, and constant time to maximum force for single movements of different amplitude--would rule out some biomechanical models of tapping speed but they do not necessarily rule out all such explanations. For example, it appears that reciprocation rate of the legs in running is related to biomechanical properties in different organisms. Once a gallop is achieved, stride frequency is rather independent of speed. Yet stride frequency decreases regularly as mass of the animal increases from mice to rats to dogs of varying size to horses (Heglund, Tayler, McMahon, 1974). Moreover, McMahon (1977) has developed a biomechanical model of these results. The application of the model is certainly not straightforward to human tapping though, because in contrast to stride frequency in animals of different mass, tapping frequency does not vary much with articulator length and mass. Still, a biomechanical constraint on tapping speed is a possibility to entertain.

Another possible constraining feature on maximum tapping speed is one of timing. There are several candidates for a timing limit. One possibility is the cycle time of a peripheral feedback loop. Kinesthetic feedback from the agonists moving the articulator in one direction might trigger movement by the antagonist in the reverse direction. Some evidence speaks against this possibility. People are able to tap quite rapidly when joint afferents are blocked by xylocaine (Provins, 1958) and when joint and tactile afferents are anesthetized by temporary blockage of bloodflow (Lazlo, 1966). In both these cases, however, muscle stretch receptors may remain operational, and those could be critical sensors. However, locomotor activity in monkeys, cats and other animals (Grillner, 1975) occur when even stretch receptors, as well as other kinesthetic senses are eliminated, but to our knowledge rapid tapping has not been studied with all major routes of kinesthesis blocked.

Perhaps the best evidence that the timing system for rapid tapping is central rather than involving a peripheral feedback loop comes from statistical analyses of the inter-response intervals. Wing (1977, 1980) has shown that a central timing model predicts a negative correlation of the durations of adjacent intervals whereas a feedback model predicts a zero correlation. For rather fast but submaximal tapping rates, Wing's evidence favors a central timer.

Wing's analysis of inter-tap variability suggests yet another possible limiting factor in tapping speed. His model postulates variability in the time duration from the output of a central pulse to actual movement of the articulator. If this so called motor delay variability is large enough relative to the interpulse intervals, the pulse sent to an agonist may on occasion reach the periphery about the same time as a later pulse sent to the antagonist intended to reverse movement. Because the two signals reach the periphery about the same time, the articulator will tense but not move. Maximum tapping rate, therefore, may be a derivative of variability in the movement system rather than due to minimum cycle time of an internal clock.

Our research has yet to properly sort out the different explanations for the correlations of maximum tapping rate of reciprocal action. Despite the uncertain origin of individual differences in the speed of reciprocal motor activity, such a speed factor appears related to the speed of handwriting and typing and may well be related to the speed of other important human motor activities.

Research Notes

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2. Hawkins, H. L., Olbirch-Rodriguez, E., Halloran, T., Ketchum, R. D., Bachman, D. B. and Reicher, G. M. Preparation cost and dual-task performance find the evidence against a general time-sharing factor. Technical Report, No. 5, Center for Cognitive and Perceptual Research, University of Oregon, 1980.

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Footnotes

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2. Complete details of the time-sharing studies by Hawkins and colleagues will appear elsewhere (Hawkins and Olbrich-Rodriguez, in preparation).

Table 1

Mean correlation of time-sharing ability between task combinations differing in 1, 2, or 3 aspects

	Exp. 1 n = 18	Exp. 2 n = 22
1 difference	r = .50	.46
2 differences	r = .34	.28
3 differences	r = .15	.05

Table 2

Correlations Between Derived Scores of Flexibility

	Prime benefit	Prime cost	Rare event	Alternating fast	Alternating fast minus Alternating slow	Dichotic Listening
Prime benefit	.89					
Prime cost	.75*	.32				
Rare event	.45*	-.20	.96			
Alternating fast	.44	-.01	.31	.87		
Alternating fast minus Alternating slow	.59*	-.20	.61*	.77*	.80	
Dichotic listening	.43	-.22	.21	.47*	.45*	.92

Underlined values are reliabilities

* $p < .05$

Table 3

Tapping Speed

	Msec./Tap	Taps/Sec.
Finger	201	5.0
Thumb	205	4.9
Wrist	160	6.3
Arm	158	6.3
Foot	198	5.1

Table 4

Correlations Between Speed of One System and Speed of Another

	Finger	Thumb	Wrist	Arm	Foot
Finger	.86	.80	.84	.69	.75
Thumb	.73	.95	.98	.79	.68
Wrist	.70	.85	.80	1.0	.74
Arm	.59	.72	.91	.86	.69
Foot	.67	.59	.64	.61	.92

Underlined vlaues are reliabilities. Values below the major diagonal are uncorrected. Those above the diagonal are corrected for attenuation.

Table 5

Correlations Between Tapping Speed and Handwriting Speed

	Uncorrected	Corrected
Finger	.54	.58
Thumb	.41	.42
Wrist	.56	.63
Arm	.52	.56
Foot	.64	.67

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